

The Araucaria Project. Infrared Tip of the Red Giant Branch Distances to Five Dwarf Galaxies in the Local Group ¹

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ABSTRACT

We have obtained accurate near-infrared photometry of the Tip of the Red Giant Branches in the Local Group galaxies Sculptor, NGC 6822, NGC 3109, IC 1613 and WLM. We have used the derived TRGB magnitudes together with the absolute magnitude calibration of the near-infrared TRGB magnitude of Valenti, Ferraro and Origlia to determine the distances of these five galaxies. The statistical errors in the distance moduli are typically 4%. The systematic uncertainties are dominated by the knowledge of the mean metallicities of the red giant branches, and are in the range of 5-8%. We observe a slight (2%) systematic difference between the distances derived from the J and K bands, respectively, which is within the 1σ errors of the distances. We compare the new distances derived in this paper with other recent distance determinations for our target

galaxies and find excellent agreement. In particular, the near-infrared TRGB distances to the four dwarf irregular galaxies in the sample agree to better than 5% in each case with their Cepheid distances obtained from infrared photometry, indicating that there is no appreciable systematic offset between these two fundamental techniques using old and young stellar populations, respectively.

Subject headings: distance scale - galaxies: individual (Sculptor, IC 1613, NGC 6822, NGC 3109, WLM, Carina, Fornax) - stars: TRGB - infrared photometry

1. Introduction

The Araucaria project is a long term program designed to improve the calibration of the cosmic distance scale by improving known, or introducing new, stellar methods of distance measurement by extensive photometric and spectroscopic observations of these standard candles in a number of galaxies in the Local Group and the nearby Sculptor Group (e.g. Gieren et al. 2005a). The methods of distance measurement we have been using and improving in the course of the project, both in the optical and near-infrared domains, include the Cepheid period-luminosity relation, the RR Lyrae period-luminosity-metallicity relation, the mean brightness of red clump stars, and the TRGB brightness (e.g. Gieren et al. 2005b, Szewczyk et al. 2008, Pietrzynski et al. 2009a, 2010). We have also designed a new spectroscopic technique to measure galaxy distances from their blue supergiant stars (Kudritzki et al. 2008), and quite recently we have started to use late-type eclipsing binary systems in the LMC to measure a near-geometrical, accurate distance to this anchor point of the distance scale (Pietrzynski et al. 2009b).

A crucial step for achieving accurate distance determinations is the reduction of the influence of weakly known error sources, like reddening and population effects, on the distance results. In many cases this can be achieved by using near-infrared observations, which has been demonstrated for red clump stars (Pietrzynski and Gieren (2002); Pietrzynski, Gieren and Udalski (2003)), Cepheids (Pietrzynski et al. (2006a); Gieren et al. (2008a, 2008b, 2009); Soszynski et al. (2006)), and for RR-Lyrae stars (Szewczyk et al. (2009) and Pietrzynski et al. (2008)). The TRGB method, originally introduced by Lee, Freedman and Madore (1993), is also an attractive tool for distance determination in the local universe. It marks the helium flash in old, low-mass stars arriving at the end of their red

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giant phase, and in a color-magnitude diagram (CMD) occurs at a well-defined luminosity. It is generally accepted that the optical I band absolute magnitude of the TRGB does not depend on age and metallicity under the condition that the stars belong to an old and low metallicity population. Several studies (e.g. Kennicutt et al. 1998; Ferrarese et al. 2000; Udalski 2000) have confirmed this conjecture, and have shown that the TRGB brightness is also insensitive to the shape of the star formation history (SFH) for old stellar populations if the mean metallicity is less than $[\text{Fe}/\text{H}] = -0.3$ dex (Barker et al. 2004). The conceptual simplicity, and the low cost in observing time together with the relatively bright absolute magnitude of the TRGB (about -4 mag for the I band) make it a useful tool for distance determination, and since the pioneering work of Lee et al. (1993) the I band brightness of the TRGB has been successfully applied to measure distances to most of the nearby galaxies (e.g. Ferrarese et al. 2000, Karachentsev et al. 2003).

Important progress was achieved by Ivanov and Borissova (2002) and Valenti, Ferraro and Origlia (2004), who calibrated the absolute near-infrared J, H and K band magnitudes of the TRGB in terms of the metallicity of the red giants. The obvious advantage of using near-infrared data is reducing the influence of the reddening on the distance result. The TRGB magnitudes in the near-infrared bands are also brighter than in the optical bands. Unfortunately, near-infrared data for nearby galaxies, deep enough to reliably measure the TRGB magnitudes are extremely scarce. Therefore this technique has so far been applied to only a very few galaxies to measure their distances (e.g. the Magellanic Clouds (Cioni et al. 2000), NGC5128 (Rejkuba 2004) and the Fornax dSph galaxy (Gullieuszik et al. 2007)). Recently, we have started to use the near-infrared TRGB technique in the Araucaria project. In a first paper (Pietrzynski et al. 2009a) we presented near-infrared TRGB distance determinations for two Local Group dwarf spheroidal galaxies, Carina and Fornax. In this paper, we extend this work to five additional Local Group galaxies for which we could collect the necessary data: the Sculptor dwarf spheroidal galaxy, and the irregular galaxies NGC 3109, NGC 6822, IC 1613 and WLM.

Our paper is organized as follows. The observations, reductions and calibrations of the data are described in the following section. Next we present the distance determinations, followed by a discussion of the errors associated to our results and a comparison of the infrared TRGB distances derived in this paper with those previously derived for these galaxies from other techniques. Finally we present a summary and final remarks.

2. Observations, Data Reduction and Calibration

The near-infrared data presented in this paper were collected with the SOFI and ISAAC infrared cameras attached to the ESO NTT and VLT telescopes on La Silla and Paranal, respectively. The field of view of SOFI (Large Field Mode) was 4.9×4.9 arcmin whereas the FOV for the ISAAC images was 2.5×2.5 arcmin.

During one non-photometric night 9 SOFI fields were observed in Sculptor, covering the main body of this galaxy. The Sculptor galaxy was already subject of earlier deep IR imaging performed by our group with NTT/SOFI (Pietrzynski et al. 2008). However, those observations were optimized for studying the faint RR Lyrae population in Sculptor, and the stars having brightnesses similar to the TRGB magnitude were saturated in these images, or fell into the nonlinear regime of the NTT camera. Therefore, in order to accurately measure the K and J band magnitudes of the TRGB in this relatively nearby galaxy we decided to follow our strategy used earlier for the Carina and Fornax galaxies, and to observe Sculptor again with the SOFI camera but now using very short individual integrations (DITs) of 1.5 s. Such short exposure times guaranteed that the TRGB brightness was well below the non-linearity limit, making very accurate photometry possible. Our data were transformed onto the standard system using about 30 common stars from the 2MASS Point Source Catalog (Wachter et al. 2003) which were found in any given SOFI field. The scatter (rms) of the calculated zero point offsets was always smaller than 0.01 mag.

Accurate near-infrared photometry was already obtained for Cepheid variables in IC 1613, NGC 6822, WLM and NGC 3109 in the course of the Araucaria project (Pietrzynski et al. 2006, Gieren et al. 2006, Gieren et al. 2008b, Soszynski et al. 2006). The images used for the Cepheid photometry turned out to be very well suited for an accurate determination of the TRGB magnitudes in these galaxies. Indeed, in each galaxy a relatively large total area was observed ensuring large numbers of RGB stars available for the photometry. The photometry is deep enough in all cases to reach 2-3 mag below the expected magnitude of the TRGB. More detailed information about the observations, and the adopted reduction and calibration procedures, can be found in the papers cited above.

The data of IC 1613, NGC 6822, WLM and NGC 3109 were calibrated onto the UKIRT system (Hawarden et al. 2001) based on extensive observations of standard stars. In order to transform this photometry onto the 2MASS photometric system, in which the calibration of the TRGB method was done, the transformations (equation 1 and 2) derived by Carpenter (2001) were used:

$$K_s^{2MASS} = K_{UKIRT} + (0.004 \pm 0.006)(J - K)_{UKIRT} + (0.002 \pm 0.004) \quad (1)$$

$$(J - K_s)^{2\text{MASS}} = (1.069 \pm 0.011)(J - K)_{\text{UKIRT}} + (-0.012 \pm 0.006) \quad (2)$$

3. Distance determination

From the photometry in the J and K bands, we have constructed the color-magnitude diagrams (CMD) for our five target galaxies. Examples are given for NGC 6822 and WLM in Fig. 1. It can be appreciated that our photometry is indeed very well suited to calculate accurate TRGB magnitudes. Red Giant Branch stars, selected from our CMDs were used to obtain the Gaussian smoothed luminosity functions, and then the TRGB brightness was calculated with a slightly modified Sobel edge-detection filter (described in detail by Sakai, Madore and Freedman 1996). In order to improve the explicitness of the filter answer, the output of the program was weighted with the original Sobel filter set for wider sampling. This technique allows to determine the TRGB magnitude with great certainty and accuracy. In order to verify the reliability of this procedure, we made comparison tests in three galaxies: Fornax, Carina and Sculptor. The TRGB brightnesses in the J and K bands for these galaxies have been obtained with both the standard Sobel edge-detection technique, and with our modified filter, and in each case very good agreement between the corresponding results (within 0.04 mag) was found (see Table 2). However, the location of the TRGB was much better pronounced and could be more easily and accurately identified with the modified algorithm, so we decided to adopt it in our project to measure the TRGB magnitudes for the target galaxies. The resulting J and K band brightnesses of the TRGB in our 5 galaxies are presented in Table 3. Exemplary luminosity functions and outputs from the modified Sobel filter are presented in Fig. 2 for NGC 6822 and WLM.

In order to calculate the absolute magnitudes of the TRGB in the J and K bands, we need the mean metallicities of the red giant populations in our target galaxies. For the Sculptor dSph galaxy, we adopt $[\text{Fe}/\text{H}] = -1.83 \pm 0.26$ dex (Clementini et al. 2005). For NGC 3109, Hidalgo et al. (2008) obtained $[\text{Fe}/\text{H}] = -1.84 \pm 0.2$ dex, which is in good agreement with Minniti et al. (1999) who found $[\text{Fe}/\text{H}] = -1.80 \pm 0.2$ dex. For the WLM dIrr galaxy, we adopt $[\text{Fe}/\text{H}] = -1.27 \pm 0.04$ dex (Leaman et al. 2009). In order to obtain the old stellar population metallicities for IC 1613 and NGC 6822, we used optical HST photometry from the Extragalactic Distance Database (Jacobs et al. 2009). Based on the colors of the RGB stars and using the calibration of Lee, Freedman and Madore (1993), metallicities of $[\text{Fe}/\text{H}] = -1.50 \pm 0.08$ dex for IC 1613, and $[\text{Fe}/\text{H}] = -1.06 \pm 0.09$ dex for NGC 6822, respectively were obtained. Consistent metallicities were reported for NGC 6822 by Zucker and Wyder (2004) ($[\text{Fe}/\text{H}] = -1.0$ dex) and IC 1613 by Lee et al. (1993) ($[\text{Fe}/\text{H}] = -1.3$ dex).

The Galactic foreground reddenings towards the galaxies were computed from the Schlegel, Finkbeiner and Davis (1998) extinction maps, and are also reported in Table 2.

To derive the absolute TRGB magnitudes for our target galaxies, we used the calibration of Valenti, Ferraro and Origlia (2004) which was obtained from extensive near-infrared observations of 24 Galactic globular clusters covering a wide metallicity range from -2.12 to -0.49 dex (equations 3 and 4), and the metallicities from Table 2.

$$M_J^{\text{TRGB}} = -5.67 - 0.31 \times [\text{Fe}/\text{H}] \quad (3)$$

$$M_K^{\text{TRGB}} = -6.98 - 0.58 \times [\text{Fe}/\text{H}] \quad (4)$$

The 1σ scatter of the datapoints about these two calibrating relations in J and K are very similar (0.20 mag and 0.18 mag, respectively; Valenti et al. 2004). The absolute magnitudes calculated from these relations, combined with our observed TRGB magnitudes corrected for reddening with the values in Table 2, led to the true distance moduli of our five target galaxies reported in Table 4.

4. Discussion

The systematic uncertainty on each of the TRGB distance determinations in Table 4 contains contributions from the photometric zero point errors (typically 0.02 - 0.03 mag), errors on the adopted extinctions (0.02 mag), and the uncertainty on the adopted metallicities (typically 0.2 dex; see previous section). With the adopted metallicity dependence of the TRGB absolute magnitude calibration (equations 3 and 4), the accuracy of the metallicity is clearly the dominant contribution to the total error budget, particularly in the K band for which the metallicity sensitivity of the TRGB absolute magnitude is about twice as strong as in the J band.

The statistical error of the Sobel edge TRGB detection technique is estimated as the Full Width at Half Maximum (FWHM) of the highest peak that marks the TRGB.

For each target galaxy, the calculated value of the total systematic and statistic uncertainty of the distance determination is given in Table 4. We note, however, that we did not take into account any contribution from possible systematic errors on the coefficients themselves in the calibration of Valenti, Ferraro, and Origlia (2004).

As can be seen in Table 4, the distance determinations in the J and K bands are

consistent with each other. The largest discrepancy occurs for IC 1613 for which the J and K band distance determinations differ by 0.12 mag (although this is still less than the one sigma error range). This discrepancy might be caused by some contamination of the red giant sample close to the tip with AGB stars. It is worth noting that our distances obtained from K band photometry are consistently slightly shorter (by some 0.04 mag) than the corresponding distances obtained from the J band photometry. While this could be a consequence of AGB star pollution affecting the K band TRGB magnitude somewhat stronger than the J band magnitude, it could also be related to the fact that some additional internal reddening is produced inside our irregular target galaxies (e.g. $E(B-V)$ in the order of 0.1 mag) which would affect the J-band TRGB magnitude somewhat stronger (e.g. make the J-band TRGB magnitude fainter) than the less affected K-band magnitude of the tip, which is what we observe in Table 4. Evidence for the existence of internal reddening in our dIrr target galaxies of this order of magnitude had come from our previous Cepheid studies, but should be mostly related to the dusty regions in which Cepheids as young stars are embedded. It is interesting to see that the smallest difference between the J-band and K-band distance modulus (0.02 mag) occurs for Sculptor, the only dwarf spheroidal galaxy in our sample which can be supposed to be free of intrinsic reddening. A yet different possible explanation for a systematic difference between the distance moduli derived from the J and K bands is coming from the uncertainties on the slopes of the metallicity terms in equations 3 and 4, which could likely introduce systematic deviations at the 2% level in the absolute magnitudes, and hence in the distance moduli. Given the small sample of galaxies in the present work we have for comparison, no clear-cut conclusion about the origin of a possible systematic difference between the J- and K-band TRGB distances is possible. Studies on an enlarged sample of galaxies might well show that there is no significant systematic difference at all.

In Table 5 we present a compilation of previous distance measurements to our target galaxies found in the literature. As can be seen, the near-infrared TRGB distances derived in this paper agree very well with other recent distance measurements. The VIJK Cepheid distances derived in the course of the Araucaria Project for the four dIrr galaxies in this study agree in each case to better than 5% with the infrared TRGB distances, the agreement being slightly better with the TRGB distances coming from the J-band photometry. This very nice agreement of a Pop. I indicator (Cepheids) with a Pop. II indicator (TRGB) is a very recomforting result which demonstrates that genuine progress has been made in the calibration of the respective techniques; it also demonstrates the importance of having taken the methods to the infrared domain where reddening is not a dominant source of systematic error as it is in optical studies.

5. Summary and Conclusions

From near-infrared photometry of stars close to the tip of the red giant branch we have derived the distances to five Local Group galaxies using the TRGB absolute magnitude-metallicity calibration in the J and K bands given by Valenti, Ferraro and Origlia (2004). Our results complement our previous distance measurements to the Carina and Fornax dwarf spheroidal galaxies based on this same technique (Pietrzynski et al. 2009a) and provide an opportunity to check on the precision of the distance determination with the TRGB method in the near-infrared domain. We find that the distances derived from the J and K band TRGB magnitudes agree within one standard deviation of the results. However, the distances derived from the TRGB magnitudes in the J band tend to have smaller systematic uncertainties because of the smaller sensitivity of the absolute J-band TRGB magnitude on the metallicity of the red giants, as compared to the K band. On the other hand, this advantage might be compensated by the smaller reddening sensitivity of the K-band TRGB distances when the method is applied to galaxies containing considerable amounts of dust.

Applying the technique on dwarf irregular galaxies has opened the possibility to make a direct comparison with the distances derived from Cepheids, as the fundamental Pop. I distance indicator. We find that the Cepheid and TRGB distances derived from near-infrared photometry agree in all (4) cases to better than 5%, leading us to conclude that the respective calibrations of the methods are accurate at this level, and that the infrared TRGB method of distance measurement, as a technique "cheap" in telescope time, is an attractive tool for distance determination, and superior to the optical version of the method because it yields distances which are basically unaffected by reddening.

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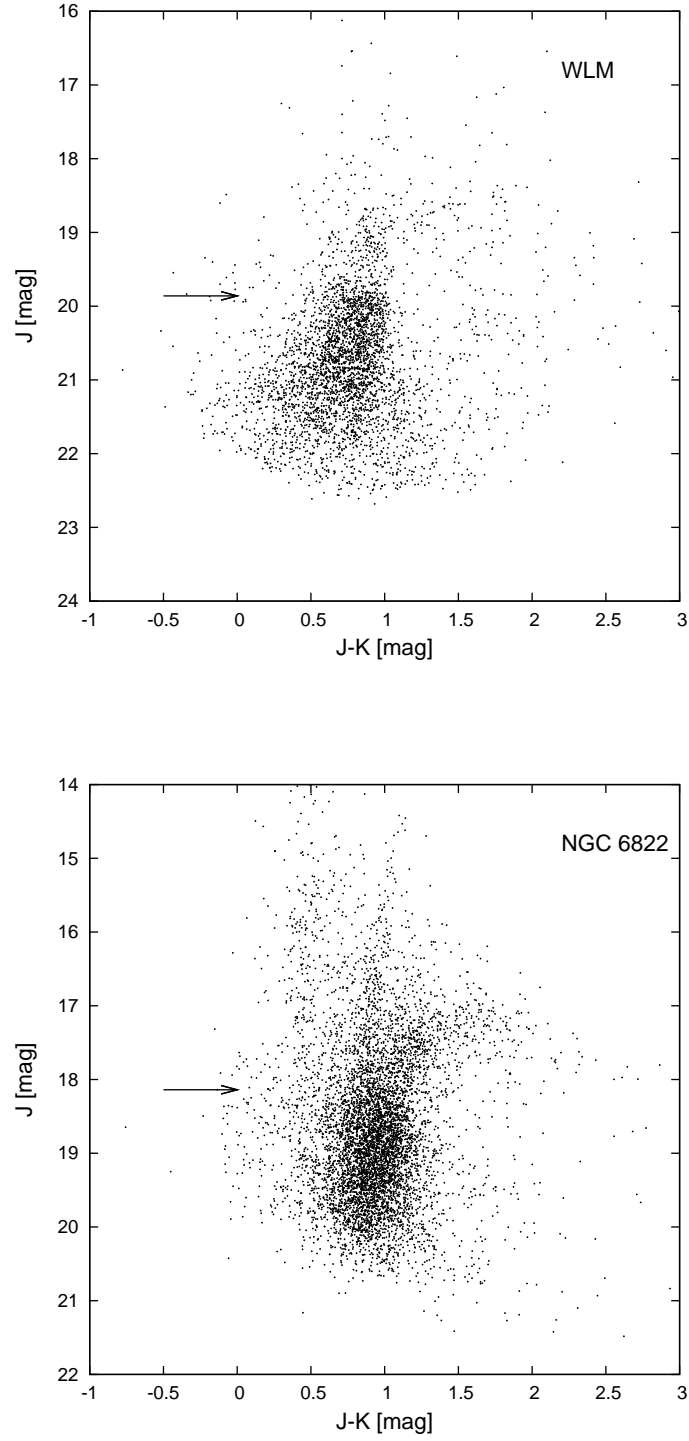


Fig. 1.— The J, J-K color-magnitude diagrams for WLM (top) and NGC 6822 (bottom) obtained from our data. The arrows point at the position of the respective TRGB magnitudes

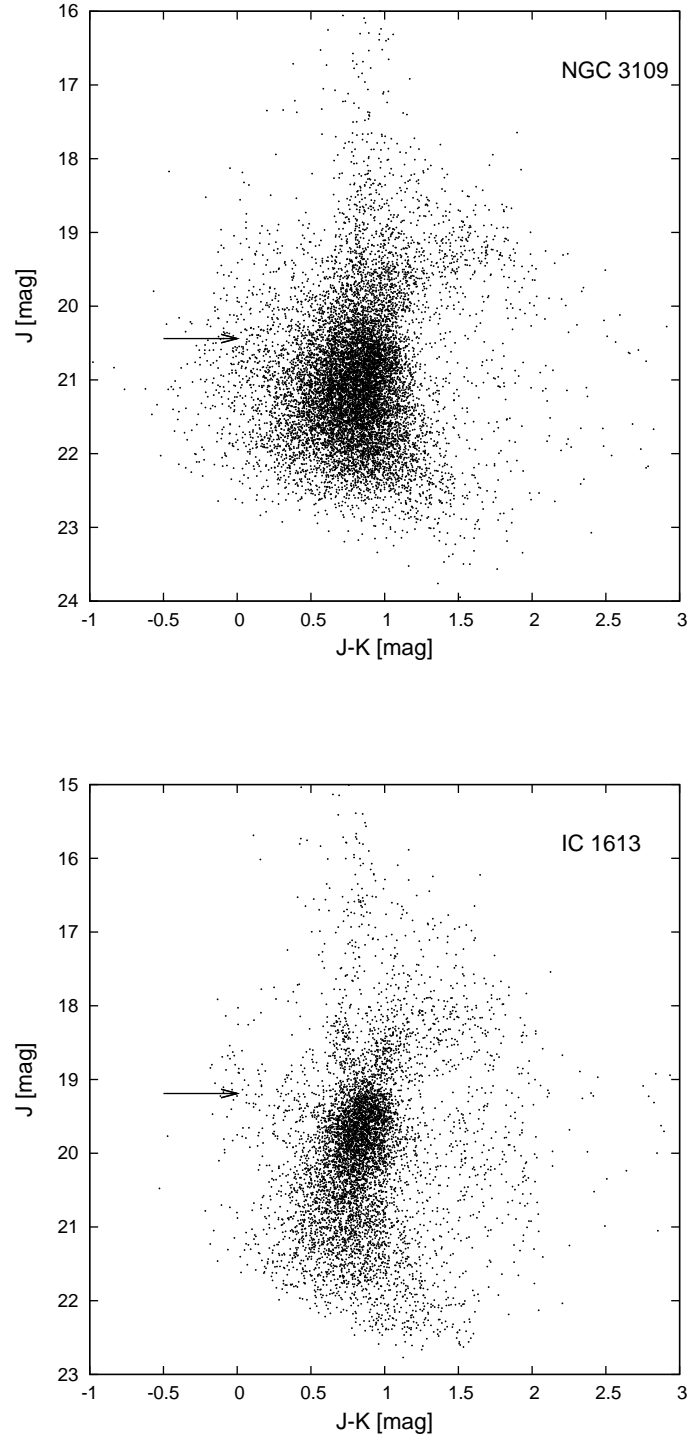


Fig. 2.— The J, J-K color-magnitude diagrams for NGC3109 (top) and IC 1613 (bottom) obtained from our data. The arrows point at the position of the respective TRGB magnitudes

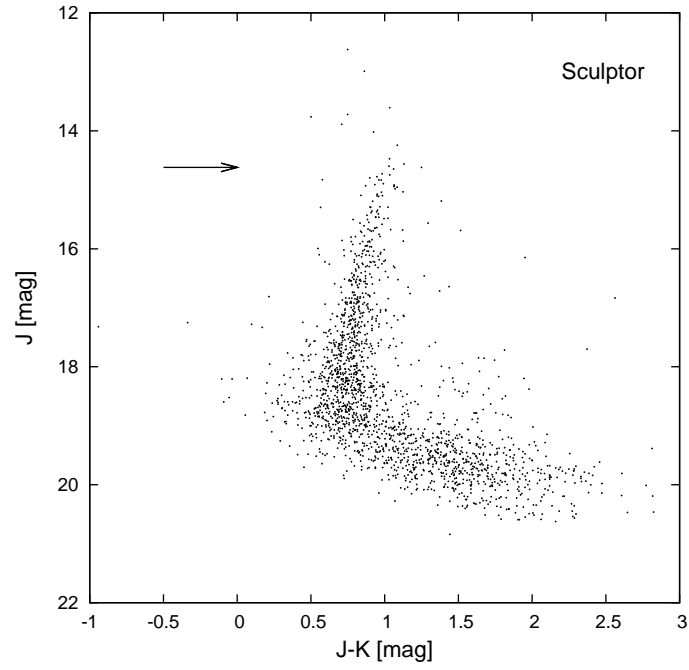


Fig. 3.— The J, J-K color-magnitude diagrams for Sculptor, obtained from our data. The arrows point at the position of the respective TRGB magnitudes

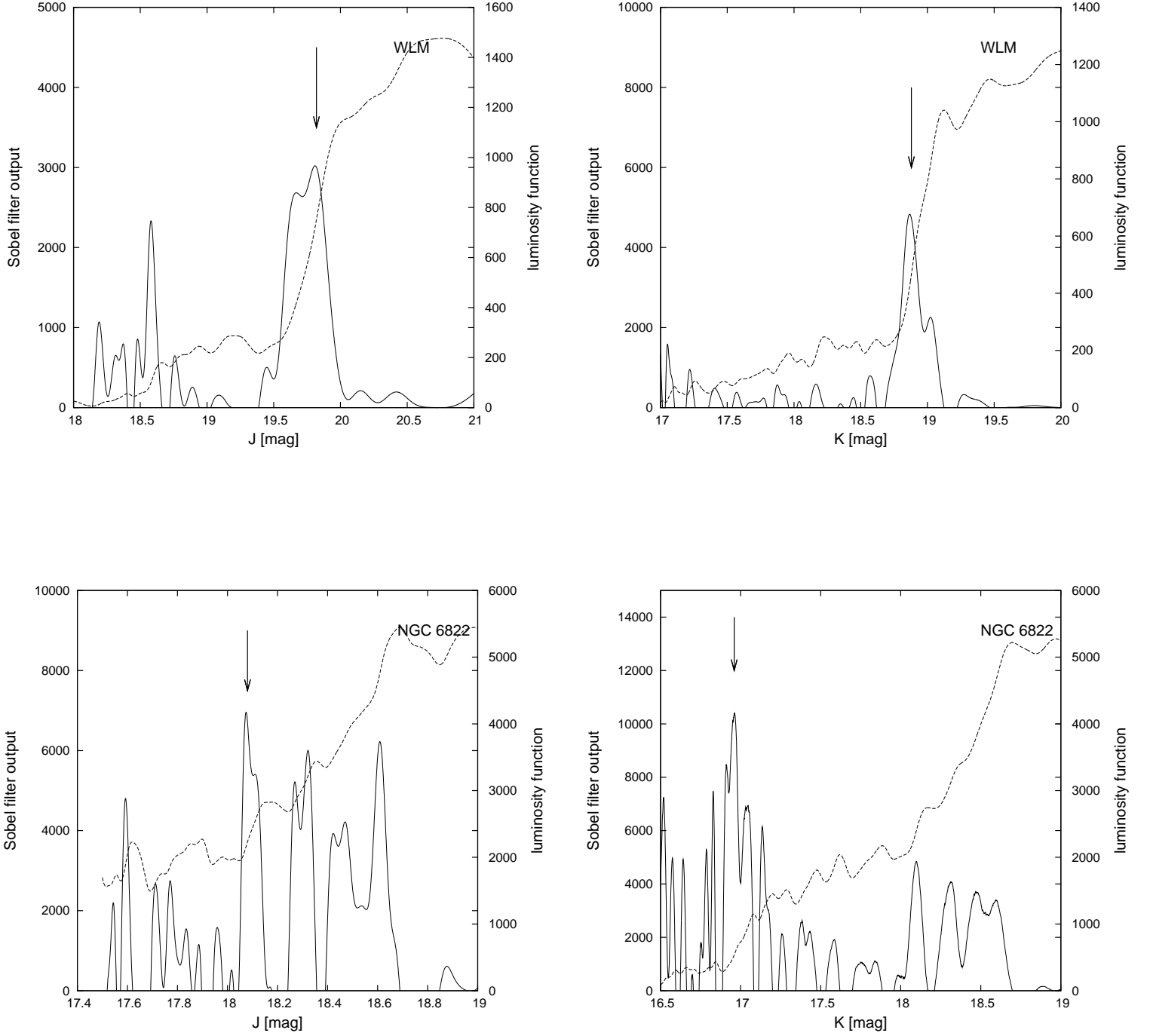


Fig. 4.— The J and K band Gaussian-smoothed luminosity function of the red giant branch (dashed line) and the corresponding outputs of the edge-detection filter (solid line) in WLM (top) and NGC 6822 (bottom). The arrows indicate the detected TRGB magnitudes.

Table 1. Near-infrared data

Galaxy	Instrument	Number of fields	Reference
Sculptor	SOFI	9	This paper
IC 1613	SOFI	8	Pietrzynski et al. (2006a)
NGC 6822	SOFI	10	Gieren et al. (2006)
NGC 3109	ISAAC	5	Soszynski et al. (2006)
WLM	SOFI	6	Gieren et al. (2008b)

Table 2. Comparison of the TRGB infrared brightnesses obtained with the modified, and original Sobel edge-detection filters for the Carina, Fornax and Sculptor galaxies.

Galaxy	Band	Original Sobel filter [mag]	Modified Sobel filter [mag]
Carina	J	15.00 ± 0.03	15.04 ± 0.04
Carina	K	14.17 ± 0.05	14.13 ± 0.09
Fornax	J	15.51 ± 0.03	15.58 ± 0.04
Fornax	K	14.45 ± 0.05	14.49 ± 0.03
Sculptor	J	14.64 ± 0.06	14.62 ± 0.08
Sculptor	K	13.82 ± 0.07	13.80 ± 0.08

Table 3. Observed J and K band TRGB magnitudes, metallicities and reddenings

Galaxy	TRGB (J) [mag]	TRGB (K) [mag]	[Fe/H] [dex]	E(B-V) [mag]
IC 1613	19.19 ± 0.08	18.13 ± 0.08	-1.50 ± 0.08	0.02 ± 0.02
NGC 6822	18.14 ± 0.05	16.97 ± 0.09	-1.00 ± 0.08	0.23 ± 0.04
NGC 3109	20.44 ± 0.05	19.52 ± 0.05	-1.84 ± 0.20	0.06 ± 0.02
WLM	19.86 ± 0.10	18.88 ± 0.08	-1.27 ± 0.04	0.04 ± 0.02
Sculptor	14.62 ± 0.08	13.80 ± 0.08	-1.83 ± 0.26	0.02 ± 0.02

Table 4. Distance moduli obtained for the target galaxies from their infrared TRGB magnitudes

Galaxy	$(m - M)_0^J$ [mag]	σ (stat.) [mag]	σ (syst.) [mag]	$(m - M)_0^K$ [mag]	σ (stat.) [mag]	σ (syst.) [mag]
IC 1613	24.36	0.08	0.09	24.24	0.08	0.10
NGC 6822	23.31	0.05	0.10	23.26	0.07	0.10
NGC 3109	25.49	0.05	0.09	25.42	0.05	0.13
WLM	25.14	0.09	0.12	25.12	0.08	0.15
Sculptor	19.72	0.08	0.11	19.70	0.08	0.17

Table 5. Distance determinations for target galaxies from different techniques

Galaxy	Method	Band	Distance Modulus	Error	Reference
			[mag]	[mag]	
IC1613	Cepheid	Mid-IR	24.27	0.02	Freedman et al. (2009)
IC1613	Cepheid	JK	24.291	0.035	Pietrzynski et al. (2006a)
IC 1613	Cepheid	V,I	24.20	0.07	Udalski et al. (2001)
IC1613	RR Lyrae	V,I	24.31	0.06	Dolphin et al. (2001)
IC1613	TRGB	I	24.38	0.05	Jacobs et al. (2009)
IC1613	TRGB	J	24.12	0.25	Jung et al. (2009)
IC1613	TRGB	H	24.20	0.44	Jung et al. (2009)
IC1613	TRGB	K	24.00	0.52	Jung et al. (2009)
NGC6822	Cepheid	JK	23.312	0.021	Gieren et al. (2006)
NGC6822	Cepheid	Mid-IR	23.49	0.03	Madore et al. (2009)
NGC6822	Cepheid	V,I	23.34	0.06	Pietrzynski et al. (2004)
NGC6822	RR Lyrae	V	23.36	0.18	Clementini et al. (2003)
NGC6822	TRGB	I	23.34	0.12	Cioni and Habing (2005)
NGC6822	TRGB	J	23.35	0.26	Sohn et al. (2008)
NGC6822	TRGB	H	23.20	0.42	Sohn et al. (2008)
NGC6822	TRGB	K	23.27	0.50	Sohn et al. (2008)
NGC3109	Cepheid	JK	25.571	0.024	Soszynski et al. (2006)
NGC3109	Cepheid	V	25.72	0.03	Pietrzynski et al. (2006b)
NGC3109	Cepheid	I	25.66	0.03	Pietrzynski et al. (2006b)
NGC3109	TRGB	I	25.45	0.15	Lee (1993)
WLM	Cepheid	V,I	25.144	0.07	Pietrzynski et al. (2007)
WLM	Cepheid	JK	24.925	0.042	Gieren et al. (2008b)
WLM	FGLR	Spectr.	24.99	0.1	Urbaneja et al. (2008)
WLM	HB	V	24.95	0.13	Rejkuba et al. (2000)
WLM	TRGB	I	24.81	-	Lee, Freedman and Madore (1993)
WLM	TRGB	I	24.85	0.08	McConnachie et al. (2005)
WLM	Cepheid	I	24.92	-	Lee, Freedman and Madore (1993)

Table 5—Continued

Galaxy	Method	Band	Distance Modulus	Error	Reference
			[mag]	[mag]	
Sculptor	RR Lyrae	J,K	19.67	0.12	Pietrzynski et. al. (2008)
Sculptor	TRGB	optical	19.64	0.08	Rizzi (2002)
Sculptor	HB	V	19.66	0.15	Rizzi (2002)
Sculptor	RR Lyrae	V	19.71	0.18	Kaluzny et al. (1995)